Technology for Space Optical Interferometry

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ABSTRACT

The Micro-Precision Control/Structure Interaction (CSI) program at JPL is chartered to develop the structures and control technology needed for sub-micron level stabilization of future optical space systems. The extreme dimensional stability required for such systems derives from the need to maintain the alignment and figure of critical optical elements to a small fraction (typically 1/20th 101 /50th) of the wavelength of detected radiation (about 0.5 micron for visible light, 0.1 micron for ultra-violet light). This λ/50 requirement is common to a broad class of optical systems including filled aperture telescopes (with monolithic or segmented primary mirrors), sparse aperture telescopes, and optical interferometers. The challenge for CSI arises when such systems become large, with spatially distributed optical elements mounted on lightweight, flexible structure. This paper will present an overview of the approach that is being taken by JPL's CSI program to address this challenge. In particular the paper will discuss the application of CSI technology to a specific example of a future large optical space mission, Experimental demonstration of the technology on ground-based testbeds will also be presented.

1. INTRODUCTION

A number of potential future NASA missions fall into the class of large optical systems addressed by]nicro-precision CSI technology. Orbiting Stellar Interferometer (0S1), Next Generation Space Telescope (NGST), Imaging Interferometer (11), Precision Optical Interferometer in Space (POINTS), Astrometric Imaging Telescope (AIT), Submillimeter Intermediate Mission (SMIM), Space Infrared Telescope Facility (SIRTF), and several proposed lunar-bawd observatories arc examples, The JPL CSI program has chosen a large optical interferometer, similar to 0S1, as representative of this mission class. An optical interferometer utilizes a number of distinct telescopes, each of modest aperture, whose outputs arc combined in such a way as to produce an effective aperture equivalent to the largest baseline distance between telescopes. Such an instrument can be used for high resolution imaging as well as extremely precise astrometry (positional mapping of the stars). Considerable effort has been devoted to developing the design of a particular optical interferometer configuration to serve as an analytic testbed on which to explore CSI methods. This fictitious, but representative, optical system has been termed the 1 'ocus Mission Interferometer (FMI). The principal challenge presented to CSI by such an instrument is the need to maintain positional tolerances between optical elements to the order of a nanometer and to do so over a structure that may span tens of meters. Open loop response of such a system to the expected spectrum of on-board disturbances can result in thousands of nanometers of motion in the optical elements.

The key to meeting this challenge is the CSI multi-layer architecture, an approach to the vibration attenuation problem that combines three layers of control: structural quieting, vibration isolation, and active optics compensation. Reference 1 details a preliminary CSI design for the FMI. Incorporating two layers of the multi-layer architecture, passive structural damping and relatively low bandwidth optical element articulation, the effect of on-board disturbances on the optical performance metric was shown to be reduced by more than an order of magnit udc. 'l'his is, however, far short of the three to four orders of magnit udc necessary to guarantee proper interferoi neter performance. The present paper reports on the progress that has been made, via the application of more advanced CSI methods and components, toward achieving the ambitious vibration attenuation requirements. Improvements have been made in each of the three layers of the CSI multi-layer architecture. Isolat ion of the primary on-board disturbance source (i .e., Hubble Space Telescope class reaction wheels) is considered, as is the effect of extending the bandwidth of the optical control loops. The passive dampers have been augmented by the introduction of active structural control via the replacement of certain structural members with active piezoelectric members.[2] These active members have embedded force and displacement sensors, and may be used not only for the. reduction of structural vibration but also for compensation of structural distortion caused by time varying thermal loads.

In addition to detailing the analytically demonstrated effectiveness of the CSI multi-layer architecture in treating the challenges presented by the FMI, the paper also reports on current and future experimental efforts on ground testbeds aimed at verif ying this performance. The.sc testbeds are useful in demonstrating not only CSI component hardware but also the software tools that have been used in system design and analysis, Finally, the paper discusses two proposed flight experiments whose purpose it is to demonstrate that CSI technology is space mission ready.

2. THE FOCUS MISSION INTERFEROMETER (FMI)

Future spacebased precision optical systems can be divided into two broad categories: interferometers, where spatially distributed "small" collecting apertures are combined to synthesize the performance of a single larger aperture; and filled aperture systems, which arc essentiall y conventional telescopes that may incorporate segmented primary mirrors duc to the difficulty (and inherent weight) of fabricating large monolithic mirrors. JPL has selected a representative optical interferometer (Figure 1) as the target application on which to focus its CSI technology development efforts - hence the name Focus Mission Interferometer (FMI). One of the principal reasons for selecting an optical interferometer is the stressing nature of the vibrat ional stability requirements that such a system demands. It is important, however, to point out that a spectrum of other precision systems (e.g., EOS instruments, SSF microgravity payloads, SIRTF, SOFIA, SMIM, lunar observatories, ctc) will also benefit from the development of Micro-Precision CSI technology. Tfrc FMI is a concrete example that allows for trade offs amongst competing CSI component technologies and for quantification of the benefits that result from the application of CSI.

ATI optical interferometer can be used for high resolution imaging as well as extremely precise astrometry (astrometry is the mapping of stellar positions in the sky). When used for imaging, the FMI's effective baseline of 24 meters would give it roughly 10 times the resolving power of the Hubble Space Telescope. Ibis translates into a resolution of 5 miliarcseconds. The basic layout of the FMI was inspired by the work of Mike Shao of JPL's Observational Systems Division. Dr. Shao currently has in operation, on Mount Wilson in Southern California, a ground based version of the FM I.

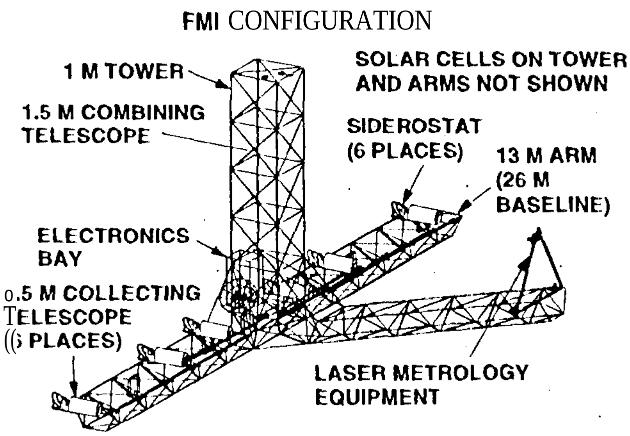

Figure 1. Focus Mission Interferometer Configuration.

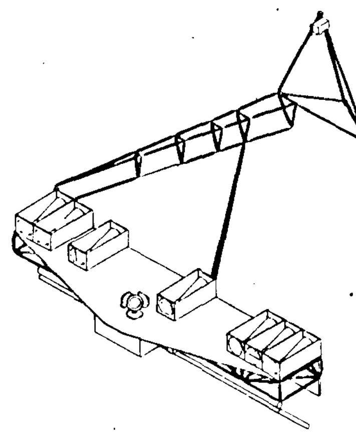

Figure 2. The Orbiting Stellar Interferometer (0S1).

The optical performance of the FMI relative to its 2.S nanometer differential pathlength stabilization requirement has been analyzed in some detail with the concision that vibration **attenuation factors of between 1,000 and 10,000** arc necessary to meet the requirement with margin. This is one of the principal challenges that CSI technology must address. Vibration attenuation alone is not sufficient, however. The need to operate well under a micron in absolute stability represents a significant challenge in its own right. In addition to exposing the severity of the performance requirements, analysis of the FM] pointed up major deficiencies in the existing capability to design and model (in an end-to-end fashion) complex opt ics/structure/control systems subjected to mechanical and thermal disturbances. This challenge must be met in order to make it practical to conduct quantitative design trades early in the design process and to enable simulation of system performance prior to fabrication and test. The final challenge is to demonstrate, to those entrusted with making NASA mission decisions, that CSI hardware, software, and methodologies arc mature and ready for application to flight systems. The remainder of this paper is organized around illustrating, in turn, how CSI is addressing each of the major challenges posed above.

It is important to note that since the 24-meter baseline FMI was conceived in 1989, the era of "faster, better, cheaper" has overtaken NASA's plans for very ambitious future astrophysics missions. Current interferometer mission studies arc focussed on 0S1, a 7-meter baseline system (Figure 2), and POINTS, a 2-meter baseline system (Figure 3). Although neither of these systems is as stressing as the FMI in terms of vibration attenuation, they still demand disturbance rejection of the order of 100:1. Thus, study of the FMI remains relevant as it instructs the vibration attenuation trade offs that will also be faced by smaller instruments.

3. MEETING THE VIBRATION ATTENUATION CHALLENGE OF THE FMI

The first challenge for an FMI class optical systems is providing three to four orders of magnitude vibration attenuation, To meet this challenge, CSI has adopted an approach that **entails a multi-layer architecture, with each layer responsible** for providing between one and two orders of magnitude attenuation. Currently three layers - vibration isolation, active/passive structural quieting, and optical element compensation - arc considered sufficient to meet the performance requirements of systems like the FM]. The idea is to intercept disturbance energy at the source (via vibration isolation), along the transmission path (via structural quieting), and at the destination (via high bandwidth optical compensation). Each layer will have a, specific realization tailored to the *system* under consideration. For the FMI, the structural quieting layer is comprised of 25 active members whose locations and elcctro-mechanical impedances have been optimized to dissipate kinetic energy from the truss structure. The vibration isolation layer is similar to that implemented on the Hubble Space Telescope (HST) reaction wheels (RW's). Improved performance, over that of} Iubble, is achieved by augmenting the HST's passive system with active control using voice coil actuators. The optical compensation layer consists of both tip/tilt control on siderostats and fast steering mirrors as well as translation control stages to correct and stabilize optical pathlength through the system, An overall closed loop bandwidth of 250 Hz has been simulated for the pathlength control loop, with a PZT providing the vernier high bandwidth actuation. For the vibration analysis, the disturbance source used was the imbalance force from 4 11ST RW's spinning from O to 3000 RPM (i.e., SO Hz).

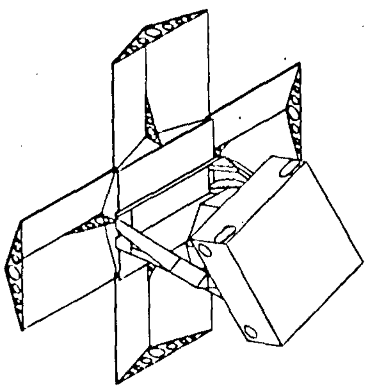

Figure 3. Precision Optical Interferometer in Space (POINTS).

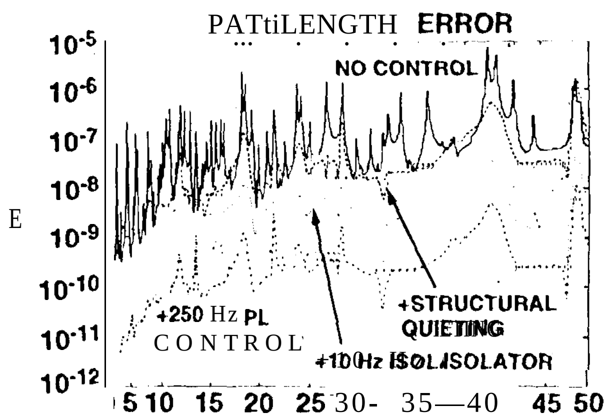

Figure 4. Optical Pathlength Control Performance on the Focus Mission Interferometer (Meters vs. Reaction Wheel Speed in Hz).

Figure 4 shows pathlength error for the FMI's outermost interferometer as a function of RW speed. Notice that, without control, the response exceeds the 2.5 nm requirement at virtuall y every RW speed, and in several speed ranges exceeds 1,000 nm. in an RMS sense, the uncontrolled pathlength response is greater than 700 nrn across all wheel speeds. As layers of control arc added - structural quieting, vibration isolation, and pathlength control, in turn - RMS vibration attenuation factors of 5, 20, and 7 arc achieved, respectively. The resultant 3-layer RMS attenuation factor of 700 means an RMS pathlength stability of just over 1 nm. In a 3-sigma sense, a worst case pathlength error of 10,000 nm is **reduced** by a factor of I ,000 to 10 nm.

Clearly, in the world of computer simulation, the CSI multi-layer architecture appears to be capable of meeting the three to four orders of magnitude vibration attenuation requirement. The next question is whether this conclusion holds up on actual physical systems under laboratory conditions.

4. EXPERIMENTAL DEMONSTRATION OF THE MULTI-LAYER ARCHITECTURE

To experimentally demonstrate that the CSI multi-layer architecture can meet this challenge, and prove that the successive layers are not unstably interactive, JPL has built a dedicated test facility called the CSI Phase B Multi-Layer Testbed.[3,4] The Phase B Testbed has been built to resemble a portion of an interferometer telescope, including a laser star simulator, a metering truss structure, an optical pathlength delay line, and the associated instrumentation and real time control computers. It has proven to be an excellent setting in which to investigate the blending of the three layers of the multi-layer architecture: structural quieting, vibration isolation, and optical compensat ion. Figure S depicts the testbed and points out each layer of control. The disturbance is mounted on a single axis vibration isolation stage. The disturbance transmissibility (i.e., transfer function) from this source to optical pathlength stability (as measured by a fringe detector monitoring the laser "star simulator" signal) represents the figure of merit for experiments conducted on the testbed.

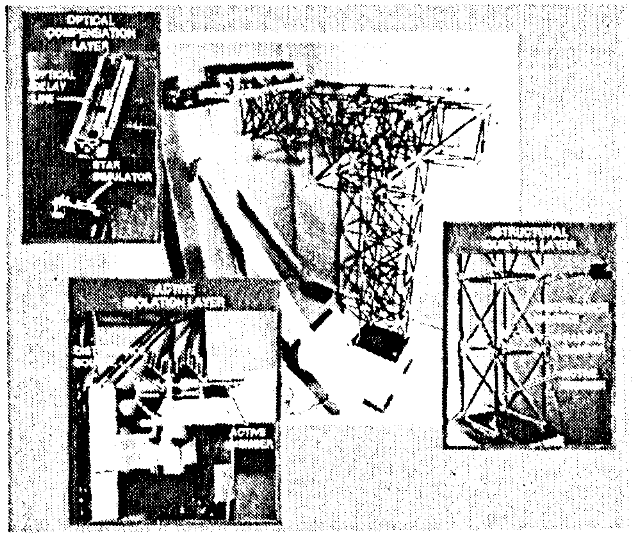

Figure 5. JPL CSI Phase B Multi-Layer Testbed.

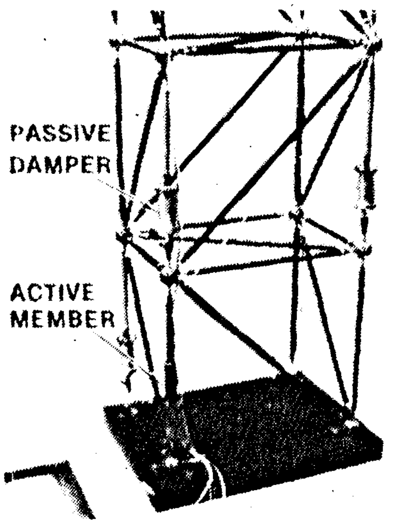

Figure 6. Structural Quieting Elements in Phase B Truss Structure.

4.1. The CSI Structural Quieting Layer

Lightl y damped resonances in structures amplify the effects of disturbances and result in much greater levels of vibration and jitter. Structural vibration in turn causes misalignment in" the optical train. Precision structures generally manifest low levels of damping because energy dissipating mechanisms such as friction are eliminated duc to the precise tolerances of the joints and connections.

The CSI structural quieting layer is specifically designed to reduce the level of vibration in the structure. This is accomplished through a combination of passive damping and active control using active structural members. Passive dampers have the advantages of simplicity of design and of requiring no power for operation. Four Honeywell D-Strut[5] passive dampers are installed in the Phase B Testbed (Figure 6). Active structural members,[6-11] which utilize an embedded piezoelectric or electrostrictive actuator, have the advantage of being tunable for optimal performance even after the structure has been assembled and/or deployed. The active dial-a-strut control circuit cannot only be tuned to emulate passive dampers, hut can also be designed to achieve a more exact impedance match to the structure, providing damping performance tailored to frequency 12 Four JPL designed active members arc installed in the testbed (Figure 6). The active and passive members have been optimally located in the structure through the use algorithms designed to minimize disturbance transmissibility from the disturbance source to the optical pathlength metric.[13,14] The performance of the structured quieting layer, in terms of disturbance attenuation, is seen by comparing the two transfer functions depicted in Figure 7. All modes below 80 Hz exhibit damping exceeding 5% of critical, compared to damping ratios between 0.1 % and 1.0% in the undamped structure. In addition to providing reduced disturbance transmission through the structure, the structural quieting layer has a stabilizing effect on the other layers of control, especiall y the high performance optical compensation la ycr. This stabilizing effect leads directly to higher bandwidth optical control, which in turns results in at least a factor of 5 improved disturbance rejection.

Recently the active member has taken a major step forward toward flight qualified status. The solid state actuator technology at the heart of the active member was flown successfully in the Actuated Fold Mirror (AFM) as part of the Hubble Recovery Mission.[15] The AFM is an optical component in the new Wide Field/Planetary Camera (WF/PC-2) which was successfully installed in the HST by astronauts in December of 1993, The AFM uses electrostrictive actuator technology, originally developed by Litton/Itek Optical Systems for Department of Defense deformable mirror applications. Because electrostrictive actuator technology is relatively new, the HST recovery mission represents its first space flight application, The research that supported the AFM for Hubble will continue to advance the readiness of precision active members that will be effective in precision alignment and structural quieting applications. The successful flight of the AFM gives tremendous impetus for incorporation of CSI active member technology in near term flight missions.

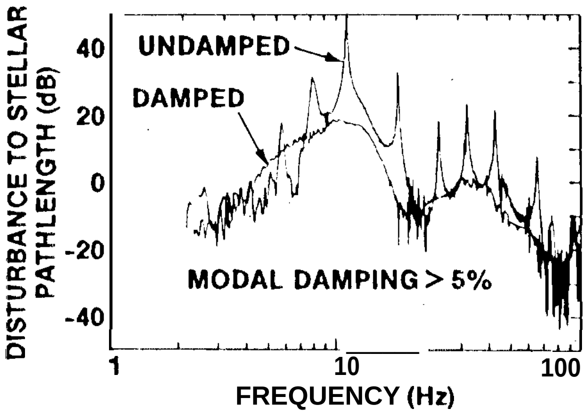

Figure 7. Disturbance Attenuation Due to the Structural Quieting Layer.

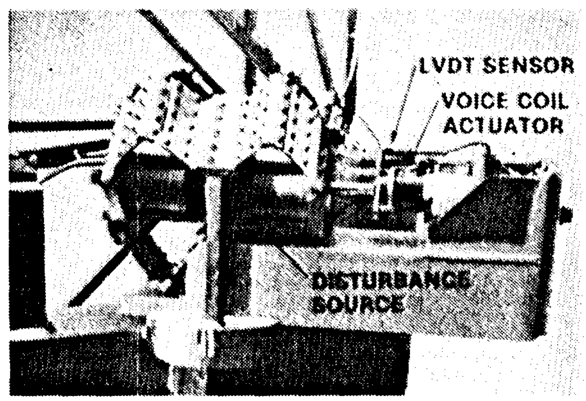

Figure 8. Phase B Testbed Disturbance isolation Fixture.

4.2. The CSI Disturbance Isolation layer

Vibration isolation is the first line of defense against the performance threatening effects of mechanical disturbances on-board micro-precision systems. For applications where the most significant disturbance sources (e.g., reaction wheels, tape recorders, ctc) can be housed together in a single "dirty box," the vibration isolation layer, in the CSI multi-layer architecture, is likely to provide the greatest performance enhancement at the lowest cost. This is because isolation can be implemented by a single six axis device, whereas the other CSI layers (viz.., structural damping and optical compensation) typical] y entail numerous hardware components distributed over the system. in such situations the vibration isolation layer, if sufficiently effective, will significantly relax the requirements on (if not eliminate the need for) one or both of the other layers. Thus motivated, the Micro-Precision CSI Program has recently placed increased emphasis on vibration isolation technology.

A disturbance isolation fixture was designed, built, and implemented on the JPL Phase B Testbed (Figure 8). 'I'he disturbance source was a proof-mass shaker suspended on an accordeon type flexure which in turn was rigidl y attached to the truss structure. The corner frequency of the soft mount was measured at 3 Hz with natural damping on the order of 12% of critical. An active stage consisting of a voice coil actuator and an LVDT displacement sensor was added in parallel with the soft mount. Active control experiments using positive position feedback (PPF) were successfull in reducing the corner frequency of the isolator by a factor of 2 over the passive design. The experimental results (Figure 9) show the improvement in optical performance when the isolator is turned on. A broadband RMS attenuation factor of greater than six was achieved.

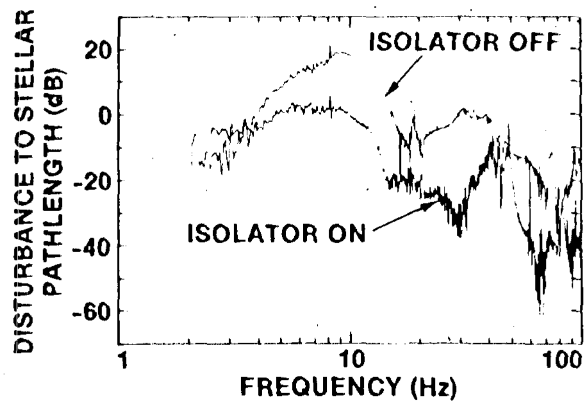

Figure 9. Disturbance Attenuation Due to the Vibration Isolation Layer.

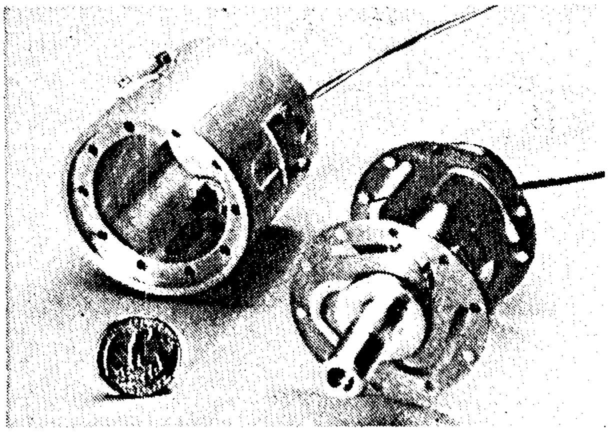
Figure 10. Soft Active Member (SAM) Isolation Strut.

Recent improvements in isolator design have enhanced this performance by another factor of five.[16] The compact single-axis device pictured in Figure 10 has demonstrated 30 dB of broadband vibration isolation (Figure 11). Plans call for building a six-axis unit consisting of six single-axis devices configured as a "Sewart Platform." In theory such a unit should be capable of fully isolating a micro-precision spacecraft from all translational and rotational disturbances. This theory will be put to the test in a proposed NASA flight experiment: the Six Axis Smart Strut Isolation Experiment (SASSIE). SASSIE is about to enter Phase A development with launch aboard the space shuttle planned for 1997.

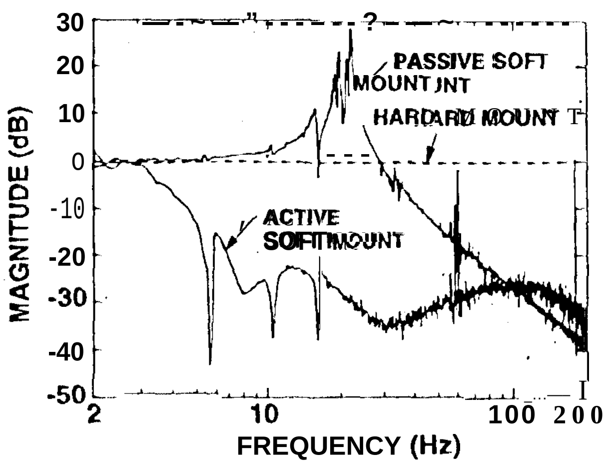

Figure 11. SAM isolation Performance.

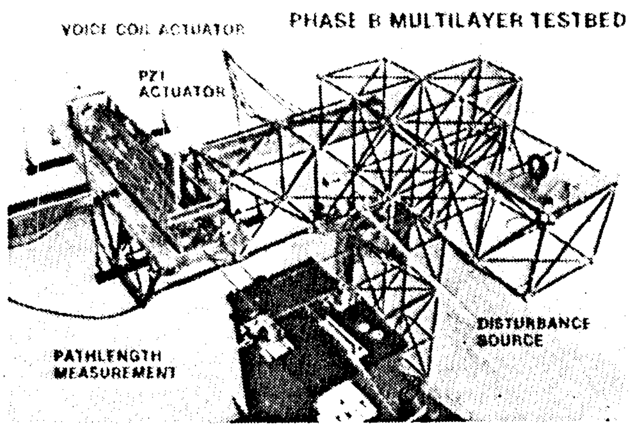

Figure 12. The Optical Compensation System on the Phase B Testbed.

4.3. The CSI Optical Compensation Layer

The optical delay line experiment was designed to capture the interaction between structural flexibility and optical pathlength as it would occur in a space-based optical interferometer such as the FMI.[17,18] Varying levels of cent.rol/strdcture interaction can be emulated by reconfiguring the testbed optical train. The configuration shown in Figure 12 represents a typical case for an interferometer, where the laser beam bounces off mirrors located on opposite ends of the truss structure. Vibrational motions of the mirrors in the path of the laser beam change the length of the optical path and this change is measured interferometrically by a fringe detector. Control of the optical pathlength is provided by a coarse motion voice coil actuator and a fine motion piezoelectric actuator.

With the testbed excited at the natural frequency of a major structural mode, closed 100P experimental results indicate (Figure 13) that stellar pathlength variations were reduced from 2.4 micrometers RMS to approximately 5 nanometers RMS (the testbed noise floor). in addition, it was demonstrated that if a white noise disturbance excited the structure with energy uniformly distributed over 1--100 Hz, the optical control layer would reject it by a factor of 139 RMS (see Figure 14).

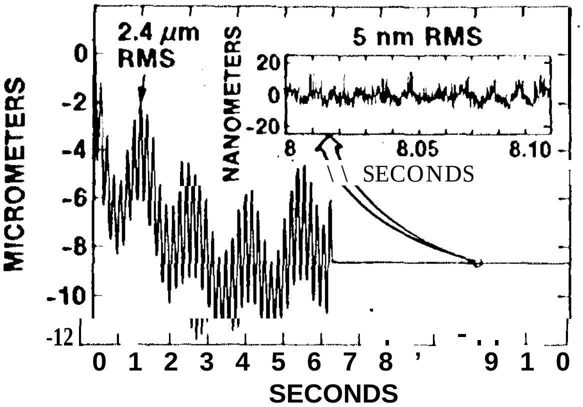

Figure 13. Optical Pathlength Response to Shaker Induced Sinusoidal Excitation - Control Loop Closed After 5 Seconds.

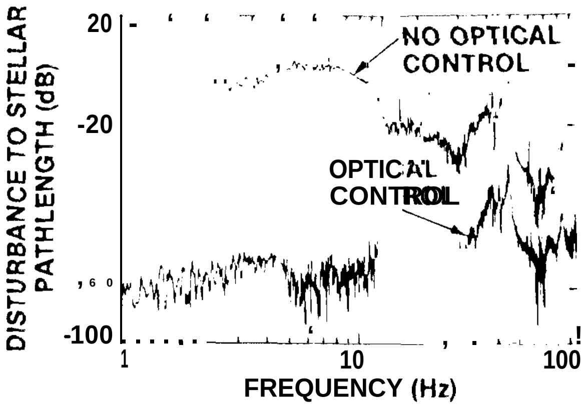

Figure 14. Disturbance Attenuation Due to the Optical Compensation layer.

4.4. Multi-Layer Performance on the Phase B Testbed

The multi-layer experimental results arc given in terms of the disturbance transmission function from disturbance source to optical pathlength. The frequency response plot of Figure 15 summarizes the results and shows how each layer, implemented successively, lowers the disturbance transmission function. Assuming that a band-limited white noise disturbance. excites the structure with energy uniformly distributed over 1--100 Hz, the RMS attenuation factor achieved by each layer in that frequency band is: (i) structural quieting: 6; (ii) disturbance isolation: 6; (iii) optical control: 139.

With all layers operating together, the multi-layer architecture enables a 5100:1 vibration reduction.[19] Clearly, the biggest contributor to vibration attenuation performance is the optical control layer. However, the structural quieting layer was essential in enabling this level of optical compensation. Without the level of damping introduced by structural quieting, the optical control bandwidth would have been reduced by at least a factor of 3 (in order to preserve system stability), resulting in a factor of 5 -10 poorer vibration attenuation. This recognition leads us to regard the optical compensation and structural quieting layers as essentially equal contributors (factor of 30 each) to overall vibration attentuation performance. Also of note is the achieved level of absolute optical pathlength stability in the ambient laboratory environment 5 nanometers RMS. The principal contributors to this residual level were fringe detector resolution (~ 2 run), noise in the control electronics, and laboratory acoustic and seismic excitation. Since the latter two noise sources are not present in space, and the former two are readily dealt with by near term improvements in electronics design, the promise of sub-nanometer stabilization of space optics appears quite feasible.

5. INTEGRATED MODELING AND DESIGN TOOLS FOR CSI SYSTEMS

The challenges facing Micro-Precision CSI do not lie exclusively in the province of developing hardware for vibration attenuation in the sub-micron regime. Work is also needed to advance the state-of-the-art for software tools for analysis and design, Existing analysis tools provide only limited capability for evaluation of spaceborne optical system designs. They determine optical performance from the geometry and material properties of the optical elements in the system, assuming only minor deviations from the nominal alignment and figure. They cannot evaluate the impact on optical performance from controlled/articulated optics, structural dynamics, and thermal response, which are important considerations for future large optics missions. TO investigate these critical relationships, a new optical system analysis tool has been developed called the Controlled Optics Modelling Package (COMP).[20,21] It is a computer program especially designed for modelling the optical line-of-sight, surface-to-surface diffraction, and full wave front performance of optical systems that are subjected to thermal and dynamic disturbances. COMP can accommodate the most common optical elements: flat and conic mirrors and lenses, reference surfaces and focal planes, as well as some uncommon optics, such as segmented and deformable mirrors. It can be used for stand alone analysis of optical tolerances and optical performance, or to provide the optics part of an integrated system model for error analysis and budgeting, or for system calibration and end-to-end simulation performance analysis. Integration of COMP with emerging CSI analysis tools will make it possible to optimize the design of a combined control/structure/optics system for maximum optical performance. All of these capabilities make COMP an important new analysis tool which enables comprehensive investigations of complex optical system architectures such as those to be used for space and Lunar bawd telescopes and interferometers. COMP has already seen application to the FMI as well as to on-going NASA flight projects including Hubble Space Telescope and SIRTF. JPI. is currently in the process of embedding COMP in a more comprehensive integrated analysis package called IMOS (Integrated Modeling of Advanced Optical Systems).22 IMOS will enable end-to-end modeling of complex optomechanical systems (including optics, controls, structural dynamics, and thermal analysis) in a single seat workstation computing environment, Version 1.0 of COMP as well as an initial version of IMOS have been completed and released, along with comprehensive User Guides. They are available through COSMIC.

The process of system design is one of synthesis. Analysis tools such as COMP and IMOS have value in this process in that they arc able to quickly evaluate competing point designs. However, analysis tools in their own right do not enable direct design synthesis. The key challenge in design synthesis is performing trade off studies pitting competing objectives from differing subsystems against one another. Too often such studies arc based solely on "engineering judgement" and are wholly non-quantitative in their approach. The more complex the system, the more likely this is to be the case. JPL has recently completed work on an initial set of software algorithms (the Integrated Design Tool) that enables quantitative trade offs across the structural, optical, and control subsystems.[23] This design tool has been used to conduct a case study on the JPL Phase B Testbed that explores the trade-off between mass and performance in precision optical systems. 'fire result is a family of testbed designs that would simultaneously provide improved optical performance and decreased mass. The current software is also capable of optimizations that include placement and tuning of damping elements, and the utilization of optical performance metrics such as Strehl ratio and wavefront error.[25,26] This design optimization methodology promises to enable the generation of highly efficient, light weight, control/structure designs required to support NASA's future optical systems.

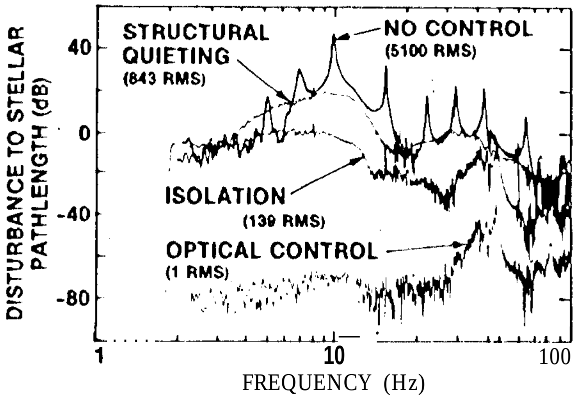

Figure 15. Disturbance Attenuation on the Phase B Testbed with All Layers Operating.

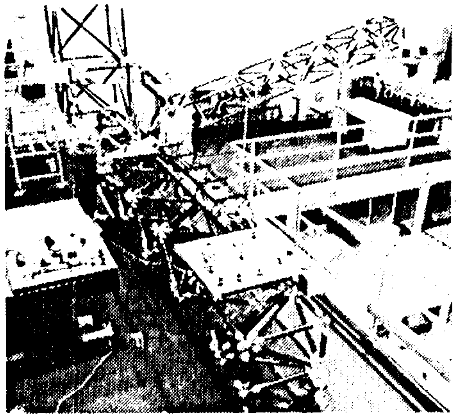

Figure 16. The Micro-Precision Interferometer (MPI) Testbed.

6. END-TO-END TESTING OF MICRO-PRECISION CSI TECHNOLOGY

To demonstrate the solution to the FMI-class control challenge, CSI technology evolution requires ground-bawd validation at the subsystem level followed by a successful demonstration of end-to-end instrument operation, first on the ground and then in space. Resulting technologies can then be applied to specific space-based interferometric missions or to other precision missions which exhibit similar challenging requirements.

6.1. The Micro-I'recision Interferometer (MPI) Testbed

The Micro-Precision Interferometer (MPI) Testbed[27-29] pictured in Figure 16 provides a crucial link, between interferometric technologies developed for ground systems and those required for spar% Its design draws upon extensive interferometer and CSI experience. The Mount Wilson Mark III Interferometer is an operational ground-bawd instrument capable of performing astrometric measurements.[30] Although overall performance is limited by the atmosphere, this facility provides a demonstration that precision alignment and control of its optical elements can be achieved when the instrument is attached to a non-flexible body such as the earth. Results from the JPL CSI Phase B Testbed, which includes a subset of the optical elements found on the Mount Wilson Mark III interferometer, demonstrate that the required nanometer level sensing and control requirements can be.achieved on a flexible structure using the CSI layered architecture.

The Micro-Precision' Interferometer Testbed allows for system integration of CSI technologies with key interferometer subsystems on a flexible structure. The MPI structure is a 7m x 6.8m x 5.5m truss weighing 200 kg (estimated to be 600 kg in its final configuration with optics and control systems attached). Built primarily from aluminum components, it went from elemental form 10 final assembly in less than four months. Considerable effort was taken in the structure assembly process to minimize alignment errors and produce a linear structure, Three linear extension springs attached to three different points on the structure make up the structure's suspension system, This system provides about a factor of ten separation between the structure's "rigid body" and flexible body modes (the lowest of which is at about 6 Hz). At this writing the M P] structure has been outfitted with a fully operational three tier delay line with associated laser metrology and real time control computer. Kinematicall y mounted optical breadboards are installed. It is to these plates that the optical pointing system components (fast steering mirrors, camera heads, fold mirrors, etc) will be mounted later this year, completing the MPI's first baseline. The testbed also has mounting hardware configured to accommodate a six axis stewart platform type isolator, also slated for delivery later this year. As currently installed, the isolator fixture, located in the bottom bay of the MPI tower, contains six rigid struts in place of the to-be-installed isolator struts.[31]

Using a "star simulator" laser metrology system located on a floated optical bench alongside the testbed, the sensitivity y of "stellar" optical pathlength (from the 'Mar," down each arm of the interferometer, and through the delay line) to mechanical excitation originating at the isolation fixture can be investigated. Figure 17 shows the transfer function from a shaker mounted on the isolation fixture to the stellar optical pathlength with the delay line control loops off. Note the testbed's lightly damped resonances (measured in previous modal surveys to have damping on the order of 0.1 %), indicative of an extremel y linear structure. Note also that, open loop, optical pathlength error exceeds 1000 nanometers per newton across a broad frequency range. By way of comparison, refer to Figure 18 for the analogous (analytically derived) transfer function for the FMI. Notice the striking similarity between the FMI and the MPI transfer functions. 'I'his, of course, is no accident. The MP1 was designed to be a half scale reproduction of a "one-armed" FMI. If there is a surprise it is that the MPI, although a considerably smaller structure, appears to be somewhat more sensitive to mechanical excitation than the FMI, perhaps indicating that analytical models of such systems err on the side of optimism in predicting system performance. This, along with a host of other issues involving hardware and software validation, will be investigated in great detail when the MPI Testbed attains full (single baseline) operational status by the end of 1994.

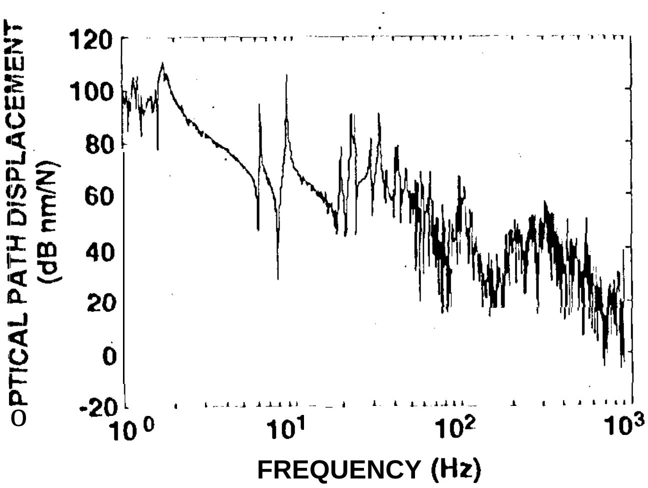

Figure 17. MPI Testbed Open Loop Transfer Function from Shaker on Isolation Fixture m Stellar Optical Pathlength (Nanometers per Newton vs. Hertz).

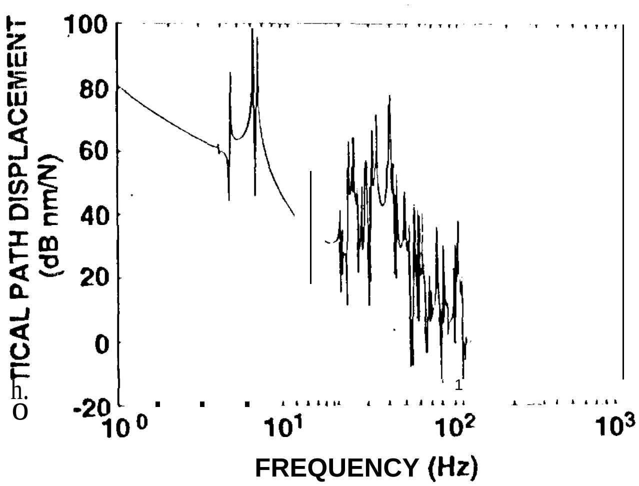

Figure 18. FMI Open Loop Transfer Function from Reaction Wheel to Stellar Optical Pathlength (Nancy eters per Newton vs. Hertz).

6.2. Flight Experiments

The MPI Testbed will go a long way toward establishing end-to-end micro-precision CSI technology readiness. However, for a handful of key components, there is no substitute for the space environment to unambiguously provide performance verification. Two examples are vibration isolation and active delay lines. For the former, testing in 1-g invariably leads to the introduction of gravity off-load mechanisms which cast doubt upon the validity of the results. Similarly for the latter, gravity plays a poorly understood role in preloading critical mechanical elements, making extrapolation from ground based to space based performance extremely difficult. prudent risk reduction in these areas indicates that testing in space is called for. Furthermore, from a psychological point of view, the excitement and impact of a space experiment should not be underestimated. "Flight proven" is a term that inspires confidence in the minds of program managers.

Two flight experiments timed at micro-precision systems technology are currentl y in the planning stages under NASA's IN-STEP (In Space Technology Experiment) Program. As mentioned above, SASSIE will explore on-orbit performance of a strut-based six-axis vibration isolation system. A more ambitious experiment, the Stellar Interferometer Tracking Experiment (SITE) will demonstrate end-to-end optical interferometer performance in the space shuttle's cargo bay. SITE will contain an optical delay line and will establish the performance credentials of this component in zero gravity.

7. SUMMANY

This paper has presented a broad brush overview of the JPL Micro-Precision CSI Program and the technology it is developing to enable future optical class NASA space missions, The program has been pursuing a plan that combines hardware development (components for sub-micron structural control, vibration isolation, and optical element articulation), sofl.ware development (integrated analysis tools such as COMP and IMOS as well as the integrated Design Tool), and the development of an overall system philosophy (viz., the CSI multi-layer architecture). To date, analytical results on the Focus Mission interferometer and experimental results on the Phase B Multi-1ayer Testbed demonstrate the promise of micTo-precision CSI technology. What remains is the demonstration of technology flight readiness via end-to-end testing on the Micro-Precision Interferometer Testbed and on-orbit demonstrations on SITE and SASSIE. This should lead to wholesale insertion of CSI technology into NASA precision space systems by early in the next decade.

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